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Application of the nitrogen-tillage-residue-management (NTRM) model for corn grown in low-input and conventional agricultural systems

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ABSTRACT

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Unlike many conventional agricultural systems, low-input management techniques minimize the use of nutrients and pesticides produced off the farm. This study evaluates the performance of the NTRM model in simulating low-input and conventionally managed field corn (*Zea mays* L.) grown in a comparative cropping systems experiment initiated in 1981 on a site in southeastern Pennsylvania, USA. NTRM is a comprehensive model that requires data on weather, soil properties, management, and crop characteristics. For our study, it predicted daily soil water, nitrogen, and temperature with depth; daily biomass and leaf area; and final grain yield. Conventionally grown corn in 1985 was used for yield calibration of the model; other data collected in 1985, 1986, and 1987 provided validation. Early model runs gave accurate soil temperature predictions but poor soil water predictions compared to field measurements. Model simulations suggested an underground water source later verified at the field site. A modification of NTRM resulted in greatly improved soil water predictions. Simulation of a hairy vetch (*Vicia villosa* Roth.) plowdown showed the need for more detailed submodels of residue incorporation and decomposition. NTRM generally provided accurate estimates of harvest biomass, grain yield, and soil NO_3–N levels throughout the season. On-going model additions, such as crop-weed interactions and intercropping, will enhance NTRM as a model for simulating low-input systems.

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INTRODUCTION

Declining commodity prices and growing public awareness of agricultural chemicals in ground and surface water have led to interest in low-input farm management systems. Low-input systems attempt to minimize inputs of synthetic fertilizers and pesticides in order to lower input costs and lessen environmental impacts. In these systems, animal and green manures improve soil fertility; crop rotations, cultivation, high crop density, and multiple cropping enhance weed control (USDA, 1980). Long-term evaluation of proposed management scenarios involving low-input systems in combination with climatic cycles can only be done with lengthy field experiments or by the application of computer simulation models. However, most crop and soil simulation models were developed for modern intensive cropping systems and have seldom been applied to low-input systems. Since these systems are heavily dependent on the rate of organic N cycling, models for simulating them require a component that adequately describes soil microbial transformations (Power and Doran, 1984).

A mechanistic soil-crop simulation model that emphasizes soil nitrogen dynamics and management decisions, NTRM (Shaffer et al., 1983; Shaffer and Larson, 1987) provided a beginning framework for modeling low-input systems. This model also has been used to make long-term projections of yield and environmental impact (Shaffer, 1985; Swan et al., 1987).

Our purpose is to evaluate the performance and utility of the NTRM model as applied to corn grown in conventional and low-input cropping systems.

METHODS AND MATERIALS

NTRM is a dynamic simulator of soil processes and crop growth using mechanistic equations and numerical methods of time and soil depth integration. For this study, we used NTRM version 3.2 dated April 1989. The model uses a process-dependent time step of 0.1 to one day, is written in Fortran 77 for the IBM Professional Fortran[1] compiler, and runs on mainframe computers, minicomputers, and IBM AT, 286, 386, and 100% compatible microcomputers. Required inputs are static site data (such as percent slope, latitude, and elevation), initial values of dynamic soil properties (such as soil water content, nitrogen, and temperature), daily weather data (maximum and minimum air temperatures, precipitation, and pan evaporation), crop characteristics (such as maturity class and growth coeffi-

[1] Mention of any specific trade name does not imply endorsement or preferential treatment by the authors, USDA, or Rodale Research Center.

cients), and management information (crop emergence dates; dates, depths, and types of tillage; and dates, types, depths of incorporation, and amounts of fertilizer, crop residue, and organic waste applications). Outputs include updated daily values for dynamic soil properties, crop biomass and grain yield, amount of runoff, and volume and NO_3–N concentration of the leachate. The soil temperature submodel (Gupta et al., 1987) numerically solves a one-dimensional heat flow equation by holding the lower boundary temperature constant and empirically estimating upper boundary soil temperatures based on daily max–min air temperatures and surface cover; it operates independently of rainfall and irrigation. The NTRM soil water submodel used in our study uses a modified piston flow approach, in which water flowing into a soil segment displaces water to the next segment once the current segment has exceeded field capacity. The rate of drainage is calculated using a first-order decay function driven by a decay coefficient and the difference between the current water content and field capacity. Crop dry-matter accumulation is driven by air and soil temperatures, and solar radiation, and is contingent on the availability of soil N and water. Crop growth coefficients for leaf area and dry matter production control the efficiency of conversion of inputs to crop biomass. The maximum rate of soil N mineralization is supplied by the user and limited by soil temperature and moisture. Details of the soil temperature, soil water flow, crop growth, and nitrogen transformation submodels together with the use and application of the NTRM model are described in detail elsewhere (Shaffer, 1985; Shaffer and Larson, 1987; Shaffer and Pierce, 1987).

A conventional and two low-input systems were part of a comparative cropping systems trial begun in 1981 at the Rodale Research Center located in southeastern Pennsylvania (Radke et al., 1988; Liebhardt et al., 1989). All cropping systems were based on five year crop rotations. One low-input system (low-input animal, LIP-A) assumed an animal component on the farm which could provide animal manures for fertilizer and organic matter applications. The second low-input system (low-input cash-grain, LIP-CG) relied on legume green manure crops to provide additional nitrogen and organic matter. The conventional system used a corn and soybean rotation with recommended rates of fertilizers and herbicides. The site (latitude 40.3° N, elevation 176 m, slope 3%) is composed primarily of Comly silt loam (Typic Fragiudalf, fine loamy, mixed, mesic) with lessor areas of Berks shaly silt loam (Typic Dystrochrept, loamy skeletal, mixed, mesic), and Duffield silt loam (Ultic Hapludalf, fine loamy, mixed, mesic). The site receives an average of 1070 mm of annual precipitation.

Corn (*Zea mays* L.) crops grown in selected treatments of the conventional and low-input treatments were modeled (Table 1). Because of low insect and disease pressures on corn at our site, none of the systems required

TABLE 1

Corn treatments (with a listing of the preceding crop and N source supplied for the corn crop) modeled for conventional, low-input cash-grain (LIP-CG) and low-input animal (LIP-A) treatments in the cropping systems experiment conducted at the Rodale Research Center near Kutztown, PA

Year	Conventional		LIP-CG		LIP-A	
	Preceding crop	N source	Preceding crop	N source	Preceding crop	N source
1985	Soybean	NH_4NO_3	Wheat	Hairy vetch		
1986	Soybean	NH_4NO_3/ urea			Red Clover	Chicken manure
1987	Corn	NH_4NO_3/ urea	Oat	Red clover/ alfalfa		

insecticides or fungicides. The nitrogen treatments considered in this paper include corn fertilized with hairy vetch (*Vicia villosa* Roth.) or red clover (*Trifolium pratense* L.) plowdowns (1985 and 1987 low-input cash-grain treatments, respectively), chicken manure (1986 low-input animal manure), split applications of ammonium nitrate fertilizer (1985 conventional), and split applications of a mixture of diammonium phosphate (DAP) and urea (1986 and 1987 conventional).

In the 1985 conventional treatment, a starter fertilizer application of 11 kg N/ha of NH_4NO_3 was applied with the seed on 29 April (calendar day 119) and a sidedressing of 139 kg N/ha of NH_4NO_3 was knifed-in as a band 10 cm to the side of the corn and 5 cm deep on 17 June (CD 168), 35 days after corn emergence.

In the 1986 conventional treatment, a starter application of 34 kg N/ha of NH_4NO_3 was applied at planting on 30 April (CD 120), and 112 kg N/ha of urea was sidedressed on 5 June (CD 156). The same amounts and types of fertilizer were applied to the 1987 conventional treatment on 1 May (CD 121) and 16 June (CD 167) for the starter and sidedress applications, respectively.

The 1985 low-input cash-grain treatment was fertilized by plowing hairy vetch (4420 kg/ha of tops dry matter) to a depth of 20 cm on 8 May (CD 128). The hairy vetch tops contained 4.1% N. Assuming the whole plant contained 40% carbon (dry weight basis) at a C : N ratio of 9.8 and the roots contained 25% of the total plant nitrogen, we estimated that the vetch added 240 kg/ha of N.

The 1986 low-input animal treatment received a heavy application of chicken manure at a rate of 421 kg N/ha on 26 April (CD 116). A sparse red clover crop was plowed under on 1 May (CD 121) as a green manure in the

1987 low-input cash-grain treatment. We calculated that the red clover tops and roots contained 54 kg N/ha at a C : N ratio of 15.

A Campbell Scientific 21X datalogger and Campbell Scientific Model 107 thermistors were used to collect hourly soil temperatures at depths of 5, 10, 30, 60, and 90 cm below the soil surface of various treatments in June, July, and August of 1986 and 1987. Soil temperatures were obtained for only certain days and only at the 5 and 90 cm depths in 1985 due to sensor installation problems, the need to use the data logger at other sites, and equipment malfunctions. Soil volumetric moisture was measured about weekly for the same months and years at depths of 8, 23, 38, 53, 76, and 107 cm by neutron attenuation with a Campbell Pacific Nuclear Corp. Model 503DR Hydroprobe moisture depth gauge.

Hairy vetch and red clover biomass samples were collected from each of the eight replicates before plowdown on 8 May (CD 128) and 1 May (CD 121) in 1985 and 1987, respectively. Two 0.5-m^2 quadrats were cut, weighed, and subsampled for moisture and nutrient content. Corn grain yield was measured by mechanically harvesting the centermost two rows of each of eight eight-row replicates. Grain moisture content was determined with a John Deere Model TY9304 moisture meter. Above ground corn biomass was estimated by taking one to four cuts of 1.5 m length from the rows immediately adjacent to the two center rows in four of the eight replicates. Leaf area index was determined from leaves on the cut plants using a Li-Cor Model 3100 leaf area meter.

Soil samples for NO_3–N analysis were obtained by pooling 15 cores (taken randomly without regard to rows, interrows, or fertilizer bands to 30 cm depth) from each of four replicates (Table 2). Samples were passed through a 2 mm sieve and 10 g soil subsamples were extracted in 100 ml of 1 N KCl (30 min shaking) followed by filtration and determination of NO_3–N by the Technicon alkaline-phenol procedure (Booth and Lobring, 1973).

MODEL CALIBRATION AND VALIDATION PROCEDURES

Before calibrating the crop growth components of the model, we determined the agreement of field measurements of soil temperature and water content with model predictions for the 1985 conventional corn treatment. Next, because the model was never previously applied to conditions and general corn varieties in southeastern Pennsylvania, the crop growth coefficients for leaf area and dry matter production were calibrated based on the 1985 corn plant data from the conventional treatment. Model validation testing was run using the 1986 and 1987 conventional and the 1985, 1986, and 1987 low-input data sets. These results provided information on NTRM model performance in situations that did not involve any model calibration.

TABLE 2

Dates of soil sampling for nitrate analyses in the conventional, low-input animal (LIP-A) and low-input cash-grain (LIP-CG) corn treatments in the Rodale cropping systems experiment for 1985, 1986 and 1987

CD	Date	Conventional	LIP-A	LIP C-G
1985				
100	APR 10	×		×
135	MAY 15	×		×
163	JUN 14	×		×
200	JUL 19	×		×
1986				
115	APR 25		×	
147	MAY 27	×	×	
156	JUN 5	×	×	
170	JUN 19	×	×	
181	JUN 30	×	×	
191	JUL 10	×	×	
201	JUL 20	×	×	
211	JUL 30	×	×	
226	AUG 14	×		
240	AUG 28	×	×	
273	SEP 30	×	×	
1987				
142	MAY 22	×		×
149	MAY 29	×		×
156	JUN 5	×		×
163	JUN 12	×		×
170	JUN 19	×		×
180	JUN 29	×		×
191	JUL 10	×		×
205	JUL 24	×		×
223	AUG 11	×		×
247	SEP 4	×		×

CD, Calendar day of the year.

RESULTS AND DISCUSSION

We have attempted to provide a critical evaluation of the NTRM model performance under true validation conditions where calibration was not done. This allows a discussion of model strengths and weaknesses, and helps to identify areas in the model and the field research program where additional work would be most beneficial.

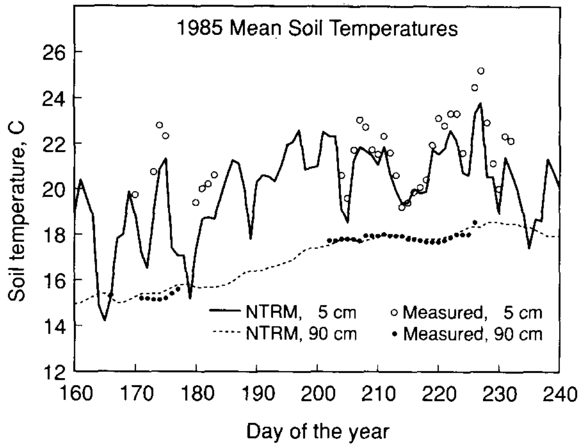

Fig. 1. Mean soil temperatures for the 5 and 90 depths predicted by the NTRM model and measured in the 1985 conventional corn treatment at the Rodale Research Center.

Soil temperature

For the 1985 conventional corn treatment, NTRM model estimates of daily average soil temperature were within 2°C of the measured data. Model estimates and field measurements for the 5 and 90 cm depths are shown in Fig. 1. Note the excellent agreement between predicted and observed results obtained for the 90 cm depth. For 1986 and 1987, NTRM predictions were within 1°C for the 5, 10, 30, 60, and 90 cm depths. A summary of a regression analysis of predicted on observed data is shown in Table 3. The r-squares and standard errors show that there was good agreement between NTRM predicted and measured soil temperatures. This suggests that the lack of interaction between the soil temperature submodel and rainfall inputs is not significant for our purposes and that empirical estimation of the upper boundary soil temperatures based on air temperature and surface cover can be used with our climate and cropping patterns.

Soil water

Upward movement of soil water (subirrigation) was required to accurately simulate soil water dynamics at our site. Initial NTRM runs without subirrigation for the 1985 and 1986 treatments predicted that the soil profile below 20 cm dried to permanent wilt (15 bar suction) by 1 August, and that the simulated crops were severely water-stressed. However, neutron probe readings indicated sufficient soil water below 20 cm throughout the growing season and negligible water stress was observed in the field. This difference

TABLE 3

Regression table for the NTRM-predicted soil temperatures regressed on the measured field soil temperatures for the conventional corn treatments in the Rodale cropping systems experiment.

Depth (cm)	n	r^2	Intercept (°C)	Slope	SE of intercept (°C)	SE of slope	SE of estimate (°C)
1985							
5	36	0.82	1.812	0.870	1.467	0.068	0.606
90	33	0.98	1.528	0.920	0.353	0.020	0.132
1986							
5	96	0.89	0.163	0.996	0.721	0.036	0.925
10	96	0.90	0.282	0.991	0.655	0.033	0.757
30	96	0.93	−1.198	1.067	0.576	0.030	0.449
60	96	0.96	−1.676	1.104	0.438	0.024	0.257
90	96	0.95	−1.093	1.072	0.436	0.025	0.224
1987							
5	127	0.93	0.070	0.956	0.474	0.023	0.882
10	144	0.96	−0.381	0.976	0.342	0.017	0.854
30	148	0.98	−0.614	0.991	0.232	0.012	0.505
60	148	0.98	−2.143	1.102	0.217	0.012	0.343
90	148	0.95	−1.866	1.095	0.376	0.022	0.480

SE, standard error; n, the number of observations.

led to field observations which indicated that subsurface lateral flow from a ridge adjacent to the plots (approximately 30 m in elevation above the plots and sloping down for 100 m) developed a shallow water table below the plots that sometimes rose to within 60 cm of the surface and maintained soil moisture at a high level.

To simulate capillary rise from a shallow water table, we modified the piston flow water submodel to allow water (and solutes) to move upward from the water table. The depth of the water table (120 cm) and width of the capillary fringe (95 cm) became model inputs. These changes greatly improved agreement between model predictions of soil water content and neutron probe measurements. For 1985 data, predicted soil water contents (θ, cm^3/cm^3) were all within 0.05 cm^3/cm^3 and within two standard deviations of the observed values (Fig. 2a and b). Similar results were obtained in 1986 (Fig. 2c and d) except somewhat larger errors occurred for the 30 cm depth between 10 May (CD 130) and 4 July (CD 185) when NTRM underestimated measured values. NTRM gave generally satisfactory soil water content predictions for 1987 except for the first five sampling dates when NTRM indicated drier soils at the 30 cm depth than were measured.

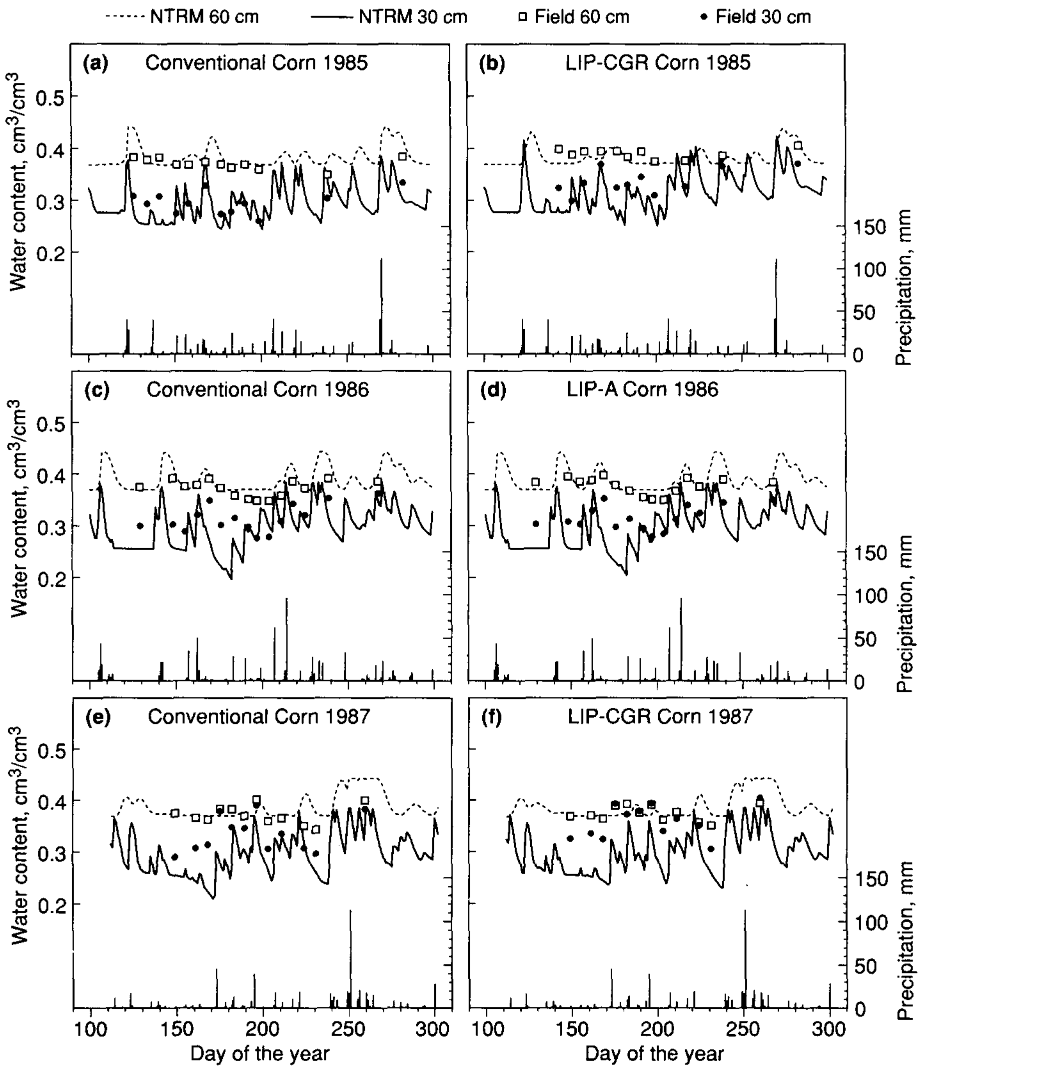

Fig. 2. Soil water contents for the 0–30 and 30–60 cm soil layers as predicted by the NTRM model and measured in the field for the indicated treatments and years. The verticle bars represent precipitation events. The model was calibrated for the 1985 conventional corn (a).

These differences may still be a reflection of lateral and upward water fluxes. In 1985, NTRM estimated 12.3 and 6.4 cm of upward movement of water from the water table for the conventional and low-input cash-grain treatments, respectively. The estimated values were 11.1 and 10.0 cm for the conventional and low-input animal treatments, respectively in 1986 and 11.1 and 10.6 cm for the conventional and low-input cash-grain treatments,

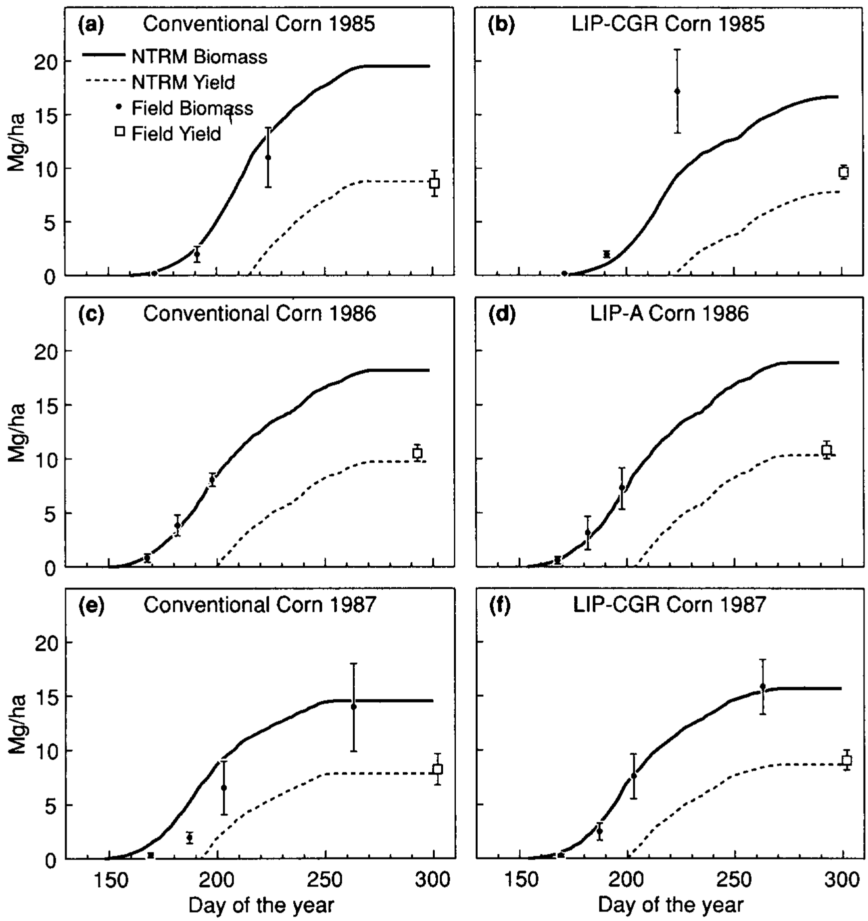

Fig. 3. Above ground biomass and grain yields as predicted by the NTRM model and measured in the field for the indicated treatments and years. The verticle bars represent plus or minus one standard deviation. The model was calibrated for the 1985 conventional corn treatment (a) and the other treatment-years provided validation data (b–f).

respectively in 1987. No field measurements of actual lateral or upward fluxes were available to verify these estimates.

Crop growth

The crop growth portion of the model was calibrated by setting the crop growth coefficients for leaf area, total dry matter production, and grain yield such that 1985 conventional corn grain yield was predicted to within 0.6% of the observed mean (Fig. 3a). The error bars represent plus or minus one standard deviation from the observed means.

Model validation results for biomass and grain yields are shown in Fig. 3b–f. In general, the model gave good agreement with observed total biomasses throughout the growing season and with final grain yields for the conventional and low-input treatments in 1986 and 1987. Biomass differences between simulated and observed were usually within one standard deviation of the field measurements for these two years. The 1987 conventional corn treatment was an exception. Apparently, cool early season temperatures retarded corn growth more in the field than in the NTRM simulation even though the model uses soil temperatures (rather than air temperatures) for the early season growth which occurs before the growing point reaches the soil surface. Predicted corn yields for all treatments in 1986 and 1987 were within one standard deviation of the measured field yields with a tendency towards under estimation. The use of a field corn variety in 1986 and 1987 that was different from the variety used in the 1985 calibration may explain some of these small differences.

NTRM had difficulty simulating mid-season biomass in the 1985 low-input cash-grain treatment (Fig. 3b). Grain yield predictions were also lower than the observed values, but showed reasonable agreement. The plowdown of a luxurious hairy vetch green manure crop resulted in very high mid-season corn biomass production and the highest corn yields of any treatment in 1985. This 1985 treatment seems to be unique within this experiment. NTRM could be recalibrated to simulate this unusual case, but that would not suit our criteria of one calibration for all treatments and years at this site. Further testing with additional data sets are needed to establish NTRM's ability or inability to simulate crop growth after large hairy vetch green manure applications.

Crop phenology calculations in NTRM are based on heat unit accumulation (10°C base). For 1985 conventional corn, time of tasseling was accurately predicted (within 3 days) and black layer formation was predicted to occur on 29 September (CD 272), although no field monitoring for black layer was done that year. For the 1985, 1986, and 1987 validation runs, corn phenology predictions of NTRM fell well within the limits of accuracy of our field data. Tasseling was predicted on 11 August (CD 223) and observed on 6 August (CD 218) for the 1985 low-input cash-grain. Predicted tasseling in 1986 was on 20 July (CD 201) and 23 July (CD 204) compared to the observed 17 July (CD 198) and 18 July (CD 199) for the conventional and low-input animal treatments, respectively. Tasseling was observed about 20 July (CD 201) in 1987 compared to predicted dates of 12 July (CD 193) and 20 July (CD 201) for the conventional and low-input cash-grain treatments, respectively. Black layer was observed in the field only in 1986 and only for the conventional treatment. Black layer was observed on 29 September (CD 272) compared to the predicted date of 1 October (CD 274).

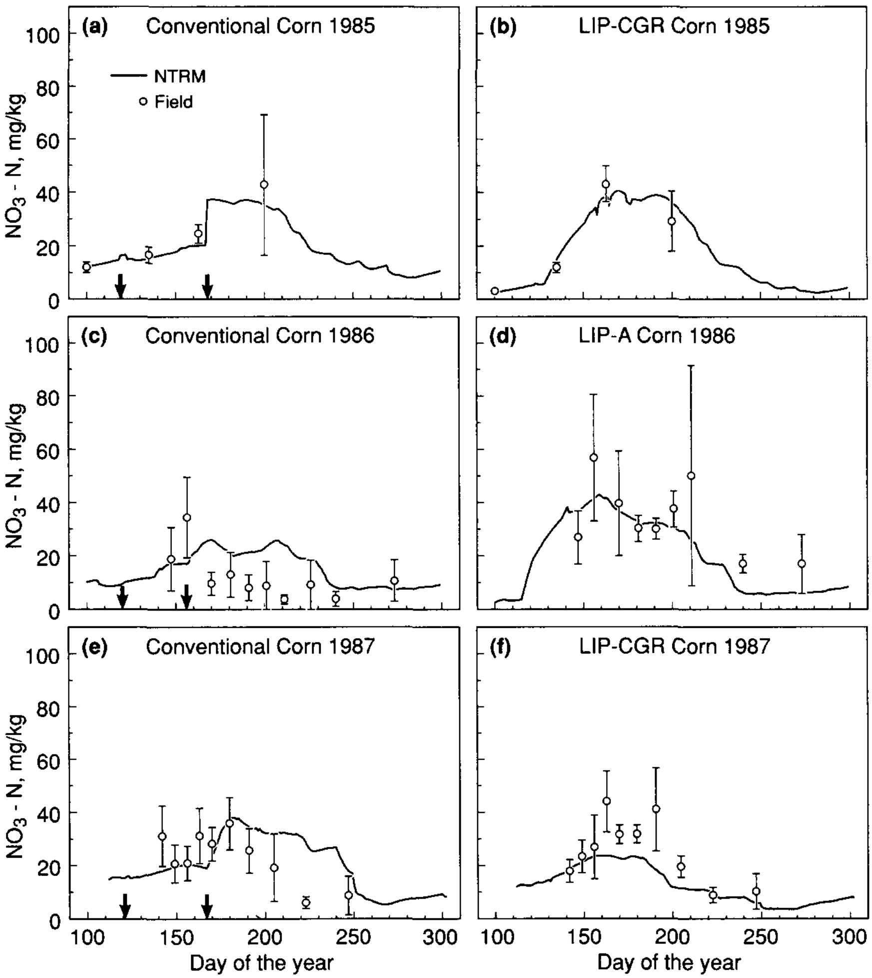

Fig. 4. Soil nitrate concentrations as predicted by the NTRM model and measured in the field for the indicated treatments and years. The verticle bars represent plus or minus one standard deviation. The model was calibrated for the 1985 conventional corn treatment (a).

Nitrate

The NTRM-predicted versus observed values of soil NO_3–N in the top 30 cm for the 1985, 1986, and 1987 conventional and low-input corn treatments are shown in Fig. 4. In 1985, the mean of the initial field measurements provided an initial value of soil NO_3–N for the model. Estimates were used for the other 2 years. We estimated the uncertainty in the field measurements by calculating the standard deviations based on eight replications for each treatment. Note the variability in the standard deviations for the various sampling dates (Fig. 4). This probably reflects how many of the individual 15 samples were taken in or near the fertilizer bands on each date. Predictions were usually within one standard deviation during the entire season for the two 1985 treatments (Fig. 4a and b) and the 1986 low-input animal treatment (Fig. 4d).

Predictions of soil NO_3–N after a sidedressing of urea in the 1986 and 1987 conventional corn treatments tended to be different from the field measurements. Field measurements showed a flush of NO_3–N soon after the sidedressing of urea followed by a fairly rapid decline; whereas, the NTRM predictions increased less rapidly after the urea applications and remained high for a longer period of time. The reason for differences between the predicted and observed values is unknown. Modifying the coefficients in the nitrification equations for urea did not significantly increase the agreement. Possible explanations include arrested nitrification in the field due to toxic effects associated with the fertilizer banding, volatilization of NH_3 from the knifed-in urea, and insufficient crop uptake of NO_3–N in the top 30 cm by NTRM. Starter and sidedressed fertilizers are actually applied in the field as bands in the row or near the row. Simulation with the one-dimensional NTRM model is based on the assumption of two uniform fertilizer applications. This did not seem to present a problem in the 1985 conventional treatment when urea was not used as a fertilizer.

In the case of the 1987 low-input cash-grain system, the poor red clover green manure crop supplied little nitrogen and that was the only nitrogen source used by NTRM other than mineralization of soil organic matter. It is likely that there was a buildup of readily mineralizable organic-N in this treatment from previous green manure applications that was not accounted for in the inputs to the model (see Radke et al., 1988). This may explain why the field measurements of biomass accumulation were higher than the NTRM predictions during the central part of the growing season. Good agreement was obtained between simulated and observed soil NO_3–N both early and late in the growing season.

CONCLUSIONS

NTRM simulated soil temperatures well even though the soil temperature submodel runs independently from the main model. While it is desirable for soil temperature calculations to interact with other variables in the model such as water flow and soil property changes, it was not necessary in our simulations.

The soil water subroutines in NTRM performed well considering the complexity of the underground water fluxes at our site. Initial NTRM runs predicted less soil water than measured in the field. Subsequent field observations indicated substantial subsurface lateral water flow. Modifications which allowed NTRM to simulate capillary rise from a shallow water table led to good agreement between predicted and measured soil water.

Above ground biomass and corn grain yields were predicted accurately in most cases. Further studies are needed for treatments with large applications of green manures such as hairy vetch. Correct timing of phenology events are very important for the proper performance of NTRM. With proper calibration, NTRM predicted tasselling and black layer dates within the accuracy of the field observations.

Soil NO_3–N is both difficult to simulate and difficult to measure in the field. NTRM gave reasonable soil NO_3–N predictions for the 1985 conventional and low-input cash-grain and the 1986 low-input animal treatments. Predicted soil NO_3–N tended to be higher than observed values after applications of urea fertilizers. Closer examination of field conditions with respect to ammonia volatilization and nitrification associated with fertilizer band placement and a review of simulated nitrogen uptake from the top 30 cm are needed to determine the cause of the difference between the simulated and observed NO_3–N.

The field sampling method used for soil NO_3–N needs refinement to reduce variability in the standard deviations observed within and between sampling dates. It is extremely important that all N sources, such as readily mineralizable soil organic matter, be accounted for in the inputs to the model. Otherwise, simulation errors such as those shown in Fig. 4f can easily occur.

NTRM gave generally good results for low-input and conventional corn treatments at our site and should be suitable for modeling similar cropping systems at other locations. Future versions of NTRM promise improved performance through the addition of subroutines for microbial activity, two-dimensional partitioning, and the effects of multiple crops, weeds, and other pests.

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